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DEVELOPMENT AND APPLICATION OF A TENDON PROSTHESIS FOR EARLY FU--ETC(U)

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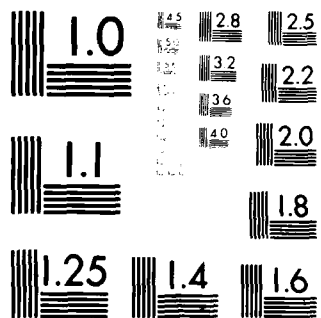
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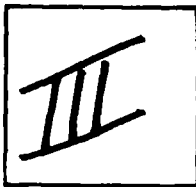
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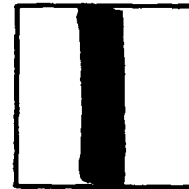
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DEVELOPMENT AND APPLICATION OF A TENDON PROSTHESIS  
FOR EARLY FUNCTIONAL RESTORATION OF THE HAND

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DEVELOPMENT AND APPLICATION OF A TENDON PROSTHESIS  
FOR EARLY FUNCTIONAL RESTORATION OF THE HAND

ANNUAL REPORT

by

James M. Hunter, M.D.

September 1975

(For the period 1 July 1974 to 30 June 1975)

Supported by

U.S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The fiber Kevlar <sup>®</sup> 49 (DuPont) was woven by Bally Ribbon Mills into 5 mm. tapes with approximate tensile strengths of 150 kg. The tape was coated with medical grade silicone (silastic) tensile tested and flex tested at the Extracorporeal Company. Test design machines were made to our speci- fications. The implant is tested at 90° of flexion with an excursion of 3 cm. 5 kg. weight, 100 cycles per minute. Preliminary toxicology in canine im- plants of porous Kevlar tape showed good tissue compatibility.		

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A tendon prosthesis with stainless steel loops was developed. The distal ends were tested by wiring with stainless steel wire through drill holes to the phalangeal bones of chimpanzees. The proximal end was fixed to tendon by a loop to loop system. This latter technique is proving not to be effective due to a tendency to a cut-through to the extreme modulus of metal loop and soft tissue looping.

Folded porous stainless steel screens with iliac bone grafts wired to the surface were studied in the dog as a method of proximal juncture in an attempt to place a changing modulus for ingrowth. Thirty kg. tensile strength at six weeks suggested that further study in this area was worthwhile as a direction for proximal end attachment.

A program was started this year to develop porous cintered titanium end devices with a direction towards permanent fixation of the tendon implant to bone and tendon.

The pseudo sheath or basic sheath formed on the surface of gliding implants was studied in depth, surgical syndactyly were created in the primates to permit one normal finger to guide two adjacent fingers with tendon implants thereby creating an excellent clinical picture. These specimens were studied at 3, 6, 9 and 12 weeks and long term sheaths to 1 1/2 years were prepared. Studies showed a synovial-like surface comparable to joint tendon sheaths synovium in the humans. Special staining suggested fluid secreting cells present along the surface of the implant.

The microvascular tendon anatomy study continued on fresh cadaver specimens. It is now believed that the fine particles of india ink latex medium is permitting study of the most basic small blood vessel capillaries. Major volar surfaces of the flexor tendon systems are apparently without distinct blood vessel supply and this study suggests that two systems of fluid nutrition take care of the flexor tendon system in the primate as well as the human. They have far reaching effects and a better understanding of tendon repair surgery. The mercurial salts ocellate continues to be studied as a tendon preservative with the possibility of tendon bank preparation for use to store tendons as Stage II replacements following the removal of tendon implants.

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**THE RESTORATION OF EARLY HAND FUNCTION, FOLLOWING TRAUMATIC INJURY  
BY THE USE OF AN ACTIVE GLIDING TENDON PROSTHESIS**

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**Title: The Development and Application of a Tendon Prosthesis for the  
Early Functional Restoration of the Injured Hand**

- 1. Type of Project: Definitive Study**
- 2. Technical Objective: The technical objective of this study is to extend the development and application of the "Hunter Tendon" so that this implant may be used as an early and permanent active tendon prosthesis following injury to the flexor tendon system in the hand.**
- 3. Hypothesis: The working hypothesis germane to this program is that an acceptable permanent prosthesis can be developed using the fundamental approach afforded by the "Hunter Tendon", a gliding artificial tendon which is moved passively.**
- 4. Background:**

**Basis and Previous Work:** During the past year the project has been reorganized into two major areas, each contributing to the overall goal of the development of a permanent flexor tendon prosthesis, and improving flexor tendon surgery in general. The results of this work are detailed on the following pages.

## I. DEVELOPMENT OF THE ACTIVE TENDON PROSTHESIS

This section deals with those Projects directly related to the development of the tendon prosthesis.

### A. The Tendon Prosthesis Shaft

The major goal of the Grant has been to develop the present commercially available passive gliding Hunter tendon implant into an active gliding tendon prosthesis. The present Hunter tendon is a woven ribbon of Dacron which is coated with vulcanized silicone rubber. This design has proved effective in thousands of clinical cases and it is therefore the basic prototype of the shaft of the active tendon. The one shortcoming of the passive tendon was that the woven Dacron core had a tensile strength of approximately 15 kg/5 mm. tape, which is not sufficient for use in an active tendon. Therefore, it was necessary to explore the possibilities of other woven materials.

The Brunsmet Co. offered us, with no cost to the Grant, a yarn of 316L stainless steel, which they had developed recently with a unique process. Mr. Bleiler at the Bally Ribbon Mill in Bally, Pa. was able to weave this yarn into a 5 mm. ribbon of tensile strength, approximately 60 kgm..

This material appeared to fulfill our requirements for tensile strength. However, as you will see discussed in a later section, there were problems with the biocompatibility of the fine 316L stainless steel yarn.

Our next possibility arose through the generosity of the Du Pont Company, which had begun production on a new polymer fiber called Kevlar<sup>(R)</sup> (see enclosure). This material is in the family of aromatic polyamide fibers known as aramids. This fiber is noted for its tensile strength, high modulus and resistance to elongation. It is three times stronger than Dacron at 430,000 psi with a per cent of elongation at breaks of 2.3% compared to 14% for type 68 Dacron.

This fiber will find use in the production of belted automobile tires, ropes and even bullet proof clothing. Despite the fact that the strongest of fibers, Kevlar 49, is very expensive, Du Pont has offered to donate as much as we need at no cost. The Du Pont Vice President, Mr. Robert Forney, in charge of the Textile Division, has offered us any technical assistance that we may require.

Mr. Bleiler has woven the Kevlar into a 5 mm. tape that tensiles out at 150 kgm.. It appears that the Kevlar will solve the problem of the tendon prosthesis woven core.

The studies that are in progress at this time are testing of the tensile flexion fatigue characteristics of the silicone-coated Kevlar ribbon. The Extracorporeal Co. has constructed and donated a machine which can simultaneously carry out these tests at 100 cycles/min. on four prostheses. The machine loads the tendons with 5 kg. weight and pulls the prosthesis through 90° flexion and an excursion of 3 cm.. This sequence is being repeated  $7.5 \times 10^6$  cycles on each prototype prosthesis to insure that the woven core is durable and that there is no loss of adherence of the silicone rubber to the woven core. We plan to build an additional machine which will stress the tendons at 25 kg..

The Du Pont fiber, Kevlar<sup>(R)</sup> is truly a fascinating polymer which may have applications in other types of prostheses. Since it is a new material, we have contacted the FDA in order to pave the way for the fiber to be accepted as an approved medical device. In this line, the Extracorporeal Company, is performing the toxicologic studies at no charge. In addition, we are engaged in a project where loosely woven Kevlar is implanted into bone and muscle tissue of dogs. Similar specimens will be tested for any change in tensile strength which would denote biodegeneration of the fiber. Other specimens will be examined histologically along with the surrounding tissue to identify any adverse reaction. The specimens were woven free of charge by Mr. Bleiler. The results will be of interest to us because of our desire to use the Kevlar in the tendon prosthesis, but the effect may be more widespread in that we will be introducing a new fiber which may have significant implications in the field of medical prostheses. Thus far, the results have been promising in that no overt foreign body reactions have occurred.

#### B. Distal Junctural Interface to Bone

The strength of an artificial tendon prosthesis is only as strong as the weakest link in the system. All previous attempts at the development of a good prosthesis have failed because of weakness at the distal or proximal junctural interface. We have investigated a number of techniques to attach the prosthesis distally to bone and have narrowed down the field to two basic concepts. These are the hard loop interface and the sintered titanium interface.

The hard-loop concept deals with essentially a loop of 316L stainless steel or titanium which is affixed to the distal end of the prosthesis. This loop is wired down to bone to produce the attachment. The concept has been proven effective in the short run in both chimpanzees and in one human opponensplasty which is still in operation ten months post-operatively. The beauty of the concept is in its simplicity, ease of attachment and removal. A large clinical trial is being planned, using a tendon prosthesis which is being produced at the Extracorporeal Co. at no charge. The major difficulties foreseen at this time with regard to the system deal with the long-term strength of the interface due to

fatigue of the wire sutures. Therefore, an alternate junctural interface, using bone ingrowth into sintered titanium is being investigated.

Dr. Jorge Galante and Dr. William Rostoker of the University of Chicago and the University of Illinois have done a great deal of excellent work in the field of bone ingrowth into sintered titanium. We have done experiments with bone ingrowth into 316 stainless steel mesh. Our experiment was designed to investigate the feasibility of using bone ingrowth in a set of circumstances which would be similar to those encountered in the phalanges of the hand. The tests were performed on dog metacarpals and, using plugs with one sq. cm. of surface area, were able to obtain tensile strengths of 50 kg/cm.. These values decreased after 12 weeks, however, due to reactivity of the 316L stainless steel. The reason for this will be discussed later, but we felt sure that we could find a less reactive metal, the concept of bone ingrowth would be a valid mechanism to provide a distal interface. This attracted us to the work of Dr. Galante and Dr. Rostoker. They were pleased to communicate with us and a fine working relationship has developed.

Professor Rostoker has agreed to do the research and development necessary to adapt his system of bone ingrowth using sintered titanium to our tendon prosthesis. He has arranged for a graduate student to work on the project. Therefore, a sub contract with the University of Illinois has been arranged with a cost of \$10,010 to our Grant. This sum will cover the graduate student's salary, University overhead and funds for the machining of the necessary dies.

It was mentioned earlier that while the experiment with the 316L stainless steel mesh proved the feasibility of bone ingrowth as a distal interface in our set of requirements, there was some difficulty with the reactivity of the 316L stainless steel after 12 weeks. It became apparent that the mesh offered a very large surface area of steel compared to its volume. In this case, even though the 316L stainless steel has a relatively low reactivity, the tissue reaction becomes significant when the surface area is large. The increased fibrous tissue encapsulating reaction resulted in a very weak tensile bond to the bone. Histological sections of the reaction are being made and the results will be published in the Fall of 1975. We feel that even though the results are negative, it is an important piece of information.

Therefore, we feel that the problem of the distal interface is solved using the hard loop and sintered titanium concepts; however, work still must be done to refine the techniques and materials.

### C. Proximal Junctural Interface to Muscle and Tendon

The most perplexing problem which has faced investigators in the past who were trying to develop an artificial tendon prosthesis, has been producing a strong, dural proximal junctural interface. In dealing with this problem, we have developed two concepts. One is the hard-loop concept and the other is a sintered titanium-bone modulus buffer interface.

The hard-loop concept is essentially the same as the hard loop used distally. The only difference is that the loop is larger and the wire is of greater diameter. This can be used when a length of proximal tendon stump is available to be threaded through the loop and sutured when the tension is correct. This mechanism has been used on chimpanzees and with success in the one human opponensplasty.

The long term effectiveness of the hard loop concept is in doubt and it cannot be used if the tendon stump is not present. Therefore, the second concept deals with a form of tissue ingrowth. Previously, other attempts at using tissue ingrowth as an interface to provide tensile strength have failed because of the difference of the Young's modulus of the soft tissue and the material which provided the porosity for ingrowth.

Bone has a modulus which is intermediate, while at the same time being compatible, biologically, with soft tissue and metal. To test the feasibility of this concept to produce a proximal interface, iliac bone grafts are wired securely to folded stainless steel mesh and implanted into the flexor carpi radialis muscle in dogs. After six weeks, the resultant interface has yielded tensile strengths of approximately 30 kg.. The inner bone grows into the mesh while the outer surfaces of the bone remodels into fibrous bone onto which the muscle heals with fibrous tissue. Therefore, there is a gradual transition from the high modulus stainless steel to the low modulus muscle. This interface is strong and because of its modulus characteristics, it should be durable. Dr. Rostoker is making some sintered titanium wafers which will be used to test the concept in the long term in a prototype active tendon. Initial publications on this unique idea will be made in early winter of 1975.

### D. Gliding Interface - the Pseudosynovial Sheath

As stated earlier, the basis of the feasibility of an active tendon prosthesis is the fact that the body will lay down a pseudosynovial sheath in response to a smooth gliding implant. This is also the basis of the Hunter passive gliding tendon implant. It was decided to do continuing work and documentation on this gliding interface in our colony of primates using histological and histochemical techniques.

Through the production of an iatrogenic syndactyly in a stump tail monkey, the normal active digit can power passive flexion in a digit containing a 3 mm. Hunter Tendon. At 3, 6, 9 and 12 weeks, sections of the pseudosheath at various levels in the fibroosseous canal and forearm have been removed. The specimens have been studied histologically using hematoxylin and eosin, PAS, and collagen staining. The same complex architecture of gliding surfaces as seen in dogs and humans was noted in the forearm specimens. However, it was also possible to see the structures that are produced in the palm area where human specimen have not been available. Here the cells are more compact, and more squamous types are seen rather than the columnar cells which occur in the wrist. The most interesting observation came in the sections stained for mucopolysaccharides. Here "goblet like" secretory cells were seen among the columnar and squamous cells. This would explain why there is lubricating fluid in the pseudosynovial sheath, but it raises another question of how endodermal secretory cell can form from a mesodermal fibroblast precursor. Much more work is necessary to elucidate the true nature of the pseudosynovial sheath, and a publication which will be complete in the Fall will further discuss the results. This work is being done by Dr. Naotsune Miyaji who has just completed an histological analysis of homograph joint transplantation at another institution.

All concepts and materials required to produce a good active gliding tendon prosthesis are known and at hand. Now the job is to refine these techniques into a clinical tool which will find great use in clinical reconstructive hand surgery.

#### RELATED WORK

## II CLINICAL PROJECTS

These projects represent work which is related to the active tendon prosthesis in that it deals with reorganizing the concepts of tendon surgery. The active tendon will not be indicated in all tendon injuries but in order to find its place, it is necessary to evaluate the other techniques which may be indicated first or complement its use. Except for the animal studies, these projects represent no added cost to the Grant, but they are discussed to give the full panorama of our thinking.

### A. Clinical Review of Delayed Primary Tendon Suture

The area between the proximal interphalangeal joint flexion crease and the distal palmar flexion crease has been known as "No Man's Land" for the repair of tendon lacerations. Dr. Lawrence Schneider at the Hand Rehabilitation Center is undertaking a retrospective clinical review of cases where primary tendon sutures have been done in this area immediately after injury and even delay up to 3 weeks. If the results are favorable, the "No Man's Land" may become "Some Man's Land" if appropriate suture techniques and post-operative hand rehabilitation are used. Using this concept, the necessity of delayed tendon grafts will be alleviated in uncomplicated tendon lacerations. An active artificial tendon would not be indicated in these cases.

## B. Cialit Preservation of Homograft Tendons

Most tendon injuries occur in young persons, the peak age is the mid-twenties, and thus this group would account for a large number of the patients requiring the artificial tendon. The prosthesis would be required to function for 50 years, thirty of which would involve significant labor. It is obvious that no prosthesis can be expected to fulfill such a long term requirement, nor would it be desirable. The major goal of an artificial tendon is to return the patient to activity as soon as possible and to maintain joint motion and muscle strength. The pseudosynovial tendon sheath is matured and the gliding tissue planes in the forearm are produced by the action of the tendon prosthesis. However, at some later time, the prosthesis should be replaced by a natural tendon graft. Since the sheath is mature and the forearm gliding planes are already present, the conversion is simple and has an excellent chance of good result.

Sources of autograft tendons are variable and may be of poor quality. Therefore an alternate supply of natural tendon grafts would be highly desirable.

Work in Europe by Karle Seiffert and recently by Francois Iselin has resulted in a promising alternate supply of tendon grafts. They preserve cadaver homograft tendons in an organic complex of mercury salts solution call Cialit. The solution maintains sterility of the tendons and appears to denature the antigenic proteins while the collagen is unaffected. Using these tendons as homografts results no rejection reaction and with time the donor collagen is infiltrated by host cells and revascularized. In effect, the homografts become an autograft. Since actual flexor tendons are used, the quality of the grafts are uniformly excellent.

We have undertaken a series of Cialit homografts among our colony of primates, in order to verify the published reports from Europe and to examine the results histologically. If we are able to reproduce their good results, this technique appears to be an excellent method of replacing the artificial tendon when that is necessary. These results will be complete by early 1976.

## C. Motion Picture to Disseminate Information on the Use of the Hunter Passive Gliding Tendon Implant.

The Hunter Tendon Implant has been found to be clinically effective in reconstructive hand surgery. However, in order for this tool to provide its ultimate benefit, it is necessary that the knowledge that is required to use the technique be available to all those qualified to use it. A one-hour 16 mm motion picture film is being made which will fulfill this purpose. The film will deal with both the operative technique and the necessary hand rehabilitation methods.

This project is being done at no cost to the Grant, but the section is included here to give an idea of how the results of the Grant combined with the other work done at the Hand Rehabilitation Center, Ltd. will lead to a significant improvement in reconstructive tendon surgery.

### III Basic Science Projects the Microcirculation of Flexor Tendons

In the development of any surgical technique and especially with regard to those involving flexor tendons, an awareness of the microcirculation is of utmost importance. Despite all the work that has been done in the last seventy-five years, very little is known of the actual architecture of the microcirculation in the flexor systems in humans and in the animal models from which the experiment tendon surgery has been done.

We are fortunate, here at Thomas Jefferson University Hospital, to have Dr. Robert J. Merklin of the Department of Anatomy. Dr. Merklin is both an authority on a special technique on microcirculation injection and he is director of the Humanitarian Gifts Registry of the Commonwealth of Pennsylvania from which we have been donated many excellent anatomical specimens for our work at no charge.

Due to his increase involvement and the importance of the injection studies, Dr. Merklin will begin to draw a salary of \$3,000 during this coming year.

The injection techniques results in a specimen which is cleared of all opaque substances except the latex-India ink solution that fills the microcirculation. This provides an excellent view of the course taken by the microcirculation down to the capillary level.

Since tendon healing is probably the results of the combination of the fibroblast derived from the pericapillary areas and the nutrition from the vessels, the implications which can be gained from a thorough knowledge of the vasculature is of extreme importance. With Dr. Merklin's help, we have undertaken a number of studies to fully elucidate this problem.

#### A. Human Foetus Circulation

This study dealt with the intrinsic microcirculation in the human foetus. The work was done by Dr. Howard Caplan. This study resulted in an entirely new understanding of tendon vasculature. A copy of his paper is enclosed for further details.

#### B. Human Adult Circulation

Through Dr. Merklin's connection with the Registry and Latitude, permitted by the Anatomy Department, we have been able to obtain fresh specimens for injection studies. The main purpose in this is to elicit any change that may occur in the vasculature with age. This will imply whether the surgical techniques must be modified by the age of the patient. This is a rather long-term study which will require a number of years to complete, but its implications are great enough to justify the time and effort.

#### C. Primate Circulation

Studies are planned which will be concerned with testing tendon suture techniques and tendon healing. Therefore, it is necessary to document the similarity of the circulatory pattern between man and lower primates. To this end, we

have injected specimens of chimpanzees and stump tail monkeys. These results will be available by September, 1975.

D. Chicken and Canine Circulation

Much of what is known of tendon surgery has been deduced from experiments done on chickens and dogs, but never has the similarity of vascular pattern between these lower animals and man be substantiated. Therefore, we are doing injection studies on these animals and the results will comment on the validity of much of that which is written on experimental tendon surgery.

# PROJECTED GOALS

1 OCTOBER 1975 to 30 SEPTEMBER 1976

PROJECT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JN	JU	AUG	SEP
<u>Prototype Active Tendon Prosthesis</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Mechanical Characteristics of Kevlar</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Bio-Compatibility of Kevlar</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Hard Loop Tendon Prosthesis</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Reactivity of Stainless Steel</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Bone Modulus Buffer Interface</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Adherence of Kevlar and Methyl Methacrylate</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Pseudosynovial Sheath</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Cialit Tendon Grafts</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Adult Human Circulation</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Primate Circulation</u>	←	←	←	←	←	←	←	←	←	←	←	←
<u>Chicken and Dog Circulation</u>	←	←	←	←	←	←	←	←	←	←	←	←

Military Significance:

Surgery of the hand had its beginning in the Army during World War II under surgeon General Kirk and Sterling Bunnell. Today in special military treatment centers, surgeons with specific training in Hand Surgery give expert care to the war wounded. Despite these programs aimed at restoring optimum hand function, time loss from injury and a high incidence of permanent disability remain as major problems. In addition, hand injuries occur at their greatest frequency in males between the ages of 18 and 26.

Significant cause of this problem are "stiff hands" and muscle atrophy that result in a part from edema and disuse of the upper extremity following severe injury.

If this vicious cycle of deterioration could be reversed early after injury, many able-bodied soldiers could be returned to active duty sooner and permanent disability could be significantly reduced.

We propose a common denominator to the return of early hand function - a tendon prosthesis that will link the silent muscles of the forearm to the resting skeleton of the hand early after injury.

This concept has become a realistic probability because of improved techniques in the early care of the injured hand, namely, 1) stabilization of hand fractures by internal fixation and 2) the recent successful military programs of delayed primary closure of severe wounds in the hand and forearm.

The significance of the injection studies lies in the fact that many simple tendon lacerations may be treated by delayed primary repair with success. However, it is necessary to elucidate the vascular pattern in the flexor system, so that suture techniques can be developed which will not endanger the blood supply. The loss of this essential blood supply accounts for the poor results using the present future techniques.

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